

A LASER BASED FUSION TEST FACILITY

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The Fusion Test Facility (FTF) is a high repetition rate ignition facility that would bridge the gap between single shot facilities (such as NIF and LMJ) and a fully functioning laser fusion power plant. It would allow development of science and technologies so that follow-on power plants could have predictable performance. The FTF would need to have enough fusion power, about 100 MW, to rigorously test materials and components for the power plants. Because inertial fusion provides a "point" source for neutrons, it can provide very high fluxes for test objects placed close to the target, while the reaction chamber walls remain at conservatively large distances. Simulations indicate that direct-drive designs can achieve 100 MW fusion power with laser energies well below 1 MJ with a 5 Hz driver. High-resolution 2-D simulations of high-velocity direct-drive implosions utilizing a Krypton-Fluoride (KrF) laser give gains of $>60\times$ at 500 kJ, and shock-ignited targets may allow higher gains at even lower driver energy. Utilizing designs that require relatively small driver energy is the most straightforward path to reducing cost and development time for a practical laser fusion energy power plant. A program to develop an FTF would build upon the science and technologies developed in the existing National Ignition Campaign and the High Average Power Laser (HAPL) program, as well as the magnetic fusion technology program.

I. INTRODUCTION

We described the basic vision of a laser based Fusion Test Facility (FTF) in "Pathway to a lower cost high repetition rate ignition facility" published in 2006 in the *Physics of Plasmas*.¹ Up until now all large scale fusion devices have had as their primary mission the development of the physics underpinnings for future fusion power plants. For inertial fusion the National Ignition Facility (NIF) and Laser Megajoule (LMJ) have sufficient energy to attain ignition and substantial gain, but only on a single shot basis (few per day). Such facilities will not be able to develop the critical

technologies needed in power plants such as high repetition operation (5-10 Hz) and wall materials that can survive the x-ray and particle emissions from high repetition fusion pellet implosions. The FTF would develop and test these critical technologies. In particular the FTF would be a source for high flux high energy neutrons that are needed to test candidate reactor materials and components. No current device, including fission reactors and ITER², can fulfill this role. While the FTF would be aimed at resolving issues for inertial fusion, it should also be useful for testing candidate materials and systems for magnetic fusion energy.

The FTF described here utilizes direct laser drive with an ultraviolet wavelength (UV) laser.³ Direct drive is the simplest and most straightforward laser approach, and it has the potential to provide sufficient gain for both the FTF and the longer term power plant application. Simulations indicate that that more than 100 MW of fusion power can be attained with a 5 Hz laser that has substantially less than a megajoule of energy. The deeper UV available with a krypton-fluoride (KrF) laser driver is advantageous towards obtaining the needed energy gain at modest driver energy.

There has been considerable progress in the pellet designs, in the driver technologies, and in our understanding of the reaction chamber issues since the 2006 paper. The original FTF concept employed higher implosion velocity to obtain predicted gains of $\sim 60\times$ at 500 kJ using a KrF laser. Numerous high resolution hydrodynamic simulations at the Naval Research Laboratory (NRL) and elsewhere have indicated that these designs are robust against hydrodynamic instability seeded by laser and target nonuniformity.⁴ These designs use higher than usual ablation pressures with a KrF laser, and that reduces the distance over which the pellet shell is accelerated. This reduced acceleration distance reduces the susceptibility of the imploding targets to disruptions by hydrodynamic instability. Experiments with the Nike laser have explored the intensities employed by these

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designs ($\sim 2 \times 10^{15}$ W/cm²) and the results indicate that KrF is effective at suppressing deleterious laser plasma instability that is not directly considered in the hydrocode simulations.⁵ Thus this original approach remains promising.

Recently the FTF pellet designs have exploited the higher performance possible with directly driven targets that are shock ignited by a final higher intensity pulse. Shock ignition allows still higher gains at reduced driver energy.⁶ In certain respects this approach is similar to Fast Ignition, in which the pellet is first compressed, and then ignited by a ~ 10 ps multi-petawatt laser pulse at intensities $\sim 10^{20}$ W/cm². With shock ignition the ignitor is a longer pulse (few hundred ps) at $\sim 10^{16}$ W/cm² that launches a converging shock to ignite the fuel. Shock ignition requires very similar laser configurations and targets to conventional direct drive. While shock ignition might allow construction of an FTF with energy less than 250 kJ, we think it prudent to plan for a facility that could achieve sufficient gain with the more conventional direct drive discussed above, while also having the capability to exploit the higher performance shock ignition.

In the following sections we discuss the progress in the physics and technological underpinnings for the FTF, and then discuss their implications on the FTF design and performance. We also briefly discuss a 3-Stage plan to develop the FTF science and technologies, FTF operation, and the prototype power plants that could follow. With technical success, the FTF (Stage II), should be able to provide enough technical operation information to allow industry to take the lead in Stage III.

Two laser technologies are applicable both to the FTF and the energy application. These include diode pumped solid state lasers (DPSSL)⁷ and KrF. Both appear to be capable of sufficient energy, efficiency and repetition rate for this application. The largest DPSSL developed for fusion is the Mercury system at Lawrence Livermore National Laboratory while the largest high repetition KrF system is the Electra Laser being developed at NRL. The DPSSL's have many similar characteristics to existing flashlamp-pumped Nd:glass lasers used in large single shot laser fusion research facilities.⁸ These lasers operate in the near Infrared ($\lambda=1053$ nm), and the shortest wavelength available with good conversion efficiency is the third harmonic ($\lambda=351$ nm). There is a well developed beam smoothing scheme called smoothing by spectral dispersion (SSD) that allows uniform illumination of targets. KrF has advantages in the target physics that include shorter wavelength ($\lambda = 248$ nm), capability for more uniform target illumination, and ability to zoom the individual beam's focal diameters to follow an imploding pellet. These advantages are projected to substantially reduce the energy of the laser

required for an FTF, to increase the target gain, and to reduce the threat from deleterious instabilities. We thus advocate and discuss herein KrF as the laser driver of choice for the FTF. That being said, we also think that it is prudent to continue to develop both laser technologies for laser fusion energy.

II. TARGET DESIGNS FOR THE FTF

We have chosen targets directly driven by laser beams for the FTF. There are a number of reasons for this choice. 1) Simulations indicate that direct drive provides sufficient gain for both the FTF and follow-on power plants. 2) There is a considerable data base from experiments that can be used to test the design codes. 3) The relatively simple targets utilized for direct drive are easier to manufacture. 4) The use of direct-drive targets minimize debris mass from the target that could erode or damage the final optics and reaction chamber wall. Indirect drive is not projected to have as high a gain as direct because of the inefficiencies involved in converting the laser light to x-rays. Our simulations indicate that shock-ignited direct drive targets can roughly match the energy gain of Fast Ignition targets.

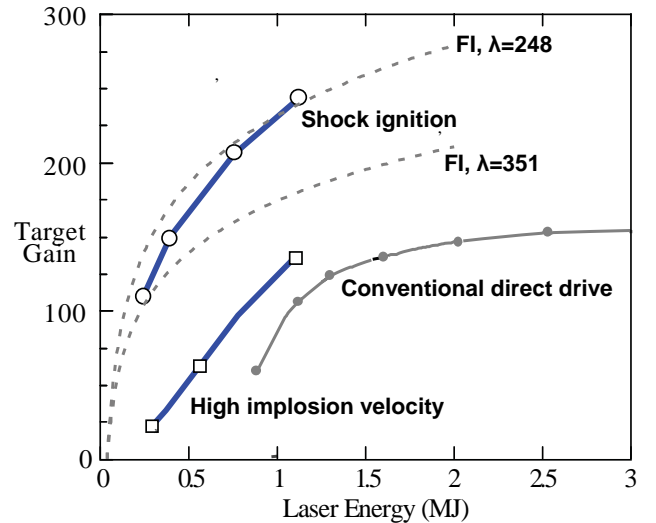


Fig. 1. 1-D calculated energy gain versus energy for various direct drive and Fast Ignition (FI) approaches. All but the one indicated FI case employ a KrF ($\lambda=248$ nm) laser. The FI gains are based on analysis in reference 10.

Details of the current FTF target designs are described in another paper in this Journal.⁹ Figure 1 shows calculated gain curves as a function of driver energy for conventional direct drive targets, high implosion velocity targets, and shock ignited targets. The latter two are candidate schemes for the FTF. For comparison the maximum gains projected for Fast Ignited (FI) targets are also presented. All but the indicated FI

curve use 248 nm light. All the direct drive designs also employ focal zooms that follow the imploding target. The conventional designs use conservative laser intensities and implode the target shell to ~ 300 km/sec. Ignition occurs at ~ 700 kJ and gains needed for energy ($\sim 140\times$ for KrF) require a few megajoules. For the "high velocity" designs, the targets are irradiated at higher peak intensities ($\sim 2\times 10^{15}$ W/cm²) to drive the shell to implosion velocities of 350-450 km/sec. The higher implosion velocities substantially reduce the laser energy required for ignition and moderately high gains. These target designs provide about $60\times$ gain at 500 kJ. High resolution 2-dimensional simulations indicate that such designs can survive hydrodynamic instability seeded by expected laser and target nonuniformities with little loss in gain.

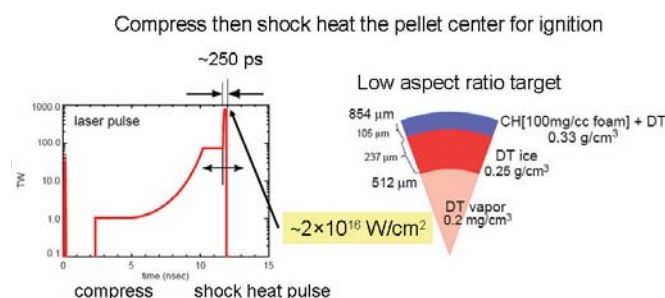


Fig. 2. Typical pulse shape and target used with shock ignition.

The shock ignition scheme provides the highest direct drive performance, with gains near $100\times$ at 250 kJ and above $200\times$ at 1 MJ. The shock ignited designs (see Fig. 2) are accelerated to sub-ignition velocities (< 300 km/sec), and the final heating of the central hot spot achieved by a converging shock launched by a final few hundred ps duration high intensity spike pulse ($\sim 1\text{--}2\times 10^{16}$ W/cm²). The use of low implosion velocity allows use of low aspect ratio (shell radius divided by shell thickness) pellets that are robust against hydrodynamic instability. The Fast Ignition gain curves in Fig. 1 assume either a KrF (248 nm) or a frequency tripled DPSSL (351nm) driver and a maximum compressed density of 300 gm/cm².¹⁰ The maximum gain for shock and fast ignition is similar at KrF's wavelength. Laser simulations indicate that the pulse shapes required for shock ignition are achievable with the standard angularly multiplexed KrF laser architecture.¹¹

The hydrocode simulations indicate that both the high velocity and shock ignited designs can fulfill the FTF mission. The shock ignited designs are especially promising and may allow gains suitable for a power plant at laser energies below 1 MJ. A target gain of $200\times$ could accommodate laser efficiencies as low as 5%. The largest

physics uncertainty in these designs is the maximum laser intensity that can be employed before the gain is compromised by deleterious laser-plasma instability. This instability can scatter the laser light and produce energetic electrons that penetrate to the fuel and impede compression. The combination of shortest wavelength, highest bandwidths, and best beam smoothing with KrF makes it the most resistant to such instability. As discussed above, recent experiments using the Nike facility support this expectation. There is ongoing experimental and theoretical work on Nike, Omega, and eventually NIF to determine these intensity limits.

III. KrF LASER PROGRESS

KrF lasers are excited dimer (Excimers) gas lasers that have a fundamental wavelength of 248 nm. Large KrF lasers are pumped by electron beams emitted from a field emission cathode driven by a fast pulsed power system. The key components of a large KrF amplifier are shown in Fig. 3. The electron beam propagates through a thin foil into the laser gas. The foil physically separates the diode region, which is at vacuum, from the laser cell, which is at atmospheric pressure or above. The structure that supports the foil is called a "hibachi." Typically two electron beams are injected into the laser cell from opposite sides. The voltage and laser gas pressure are adjusted to give a flat deposition profile across the laser cell. In a repetitively pulsed system a recirculator cools and quiets the laser gas between shots. An external magnetic field prevents the electron beam from self pinching as it propagates through the vacuum diode, and guides it through the laser-gas cell. Further details can be found in the references¹²

KrF lasers are an attractive choice for a fusion driver from both target physics and power plant perspectives. As discussed earlier, they can provide highly uniform illumination of targets; they have a short wavelength (248 nm) that increases the rocket efficiency and raises the threshold for deleterious laser-plasma instabilities; and they have the ready capability for "zooming", (decreasing the spot size to follow an imploding pellet and increase the coupling efficiency). These advantages have been recognized for many years, however the KrF technology was considered to be more challenging than the ubiquitous flashlamp pumped ND:glass lasers, and that perception has limited their use in ICF research. These challenges have been largely overcome. Moreover, from the perspective of a fusion power plant, the gas laser medium is more durable and easier to cool; and the pulsed power has the potential to be a robust and efficient industrial technology.

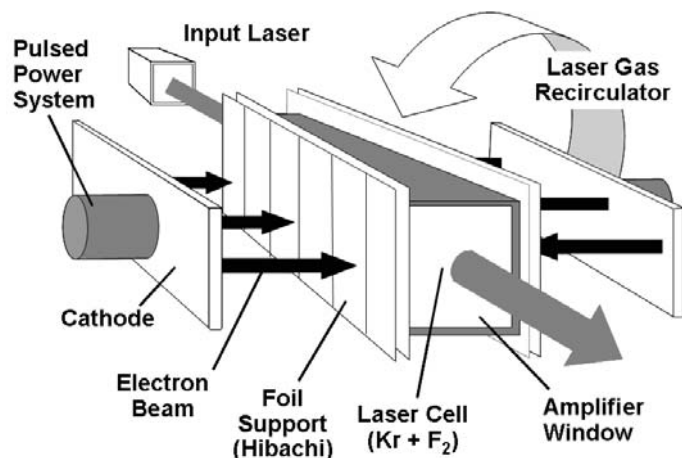


Fig. 3. Key components of an electron beam pumped KrF amplifier.

KrF laser research at NRL is carried out on two facilities, Nike¹³ and Electra.¹⁴ Both feature a discharge laser front end, two electron-beam-pumped amplifiers and angular multiplexing. Nike produces 3 to 5 kJ of laser light, and is the only high energy laser that has simultaneously demonstrated the beam smoothing, high bandwidth and deep UV that are advantageous for direct drive high gain targets. Nike was built to establish the scientific underpinnings for the fusion energy target designs, as well as study electron beam physics and technology at or near FTF and/or power plant scales. The main amplifier is pumped with two 600 kV, 540 kA, 250 nsec electron beams, has a laser aperture of 60 cm x 60 cm and an electron beam area of 60 cm x 200 cm. This is nearly the same size as one option for an FTF amplifier that is described later.

With Nike the image of a uniformly illuminated aperture in the front end is relayed through the amplifier system onto the target. One changes the focal diameter by changing the diameter of this aperture. Zooming can be achieved by combining suitably delayed laser beams that have passed through progressively smaller apertures. The apparatus needed to demonstrate temporal zooming has been installed on Nike and the results will be presented elsewhere. Tests with the Nike system at full energy indicate that the net optical aberrations are less than 8 times diffraction limit (XDL). No appreciable aberration is introduced by energizing the e-beam pumped amplifiers. This optical quality is sufficient to obtain good illumination of pellets with the planned ~100XDL induced-spatial-incoherence (ISI) smoothed laser beams planned for the FTF.

Electra is a 300–700 J repetitively pulsed system that is being used to develop the technologies that meet the fusion requirements for rep-rate, durability, efficiency and cost. A photo of the Electra Main Amplifier is shown in

Fig. 4. The main amplifier is pumped with two 500 kV, 100 kA, 140 nsec electron beams, and has a laser aperture of 30 cm x 30 cm. Electra has demonstrated rep-rate operation at 2.5 and 5 Hz, and has run continuously for over 90,000 shots. 10,000 shot runs are common, and the total number of rep-rate, high energy laser shots exceeds 400,000. Figure 5 shows results from a 10,000 shot, 2.5 Hz run in which every 1000th shots is overlaid. The laser energy is 280 J, and is very consistent over this long run

The present limit on continuous run duration is primarily the durability of the hibachi foil. Progress in extending its lifetime is discussed below. A wallplug efficiency of around 7% is predicted for a full scale (FTF) size system, based on advances with the individual components and subsystems. This should be adequate for the energy application given the progress in the target physics discussed in this paper. The following paragraphs discuss the advances in the science and technology needed for KrF lasers for fusion energy.



Fig. 4. Electra 30-cm aperture main amplifier.

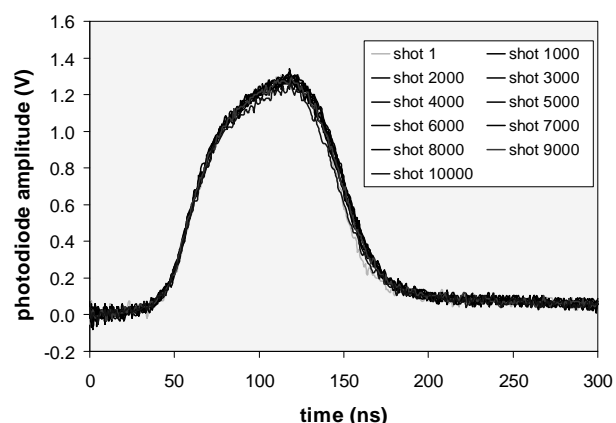


Fig. 5. Data from a 10,000 shot run at 2.5 Hz. Every 1000th shot is overlaid.

Pulsed Power: The current pulsed power system on the Electra main amplifier is based on spark gap switches

and has a useful lifetime of around 100,000 shots¹⁵ before requiring refurbishment. The limiting factor is electrode erosion, which is endemic to this type of architecture. We are developing a second generation all solid state pulsed power architecture that should meet the IFE durability requirements (> 300 M shots continuous) with the required efficiency ($> 85\%$). The essential elements are long-life capacitors, saturable magnetic inductors, and electrically triggered fast-rise-time solid state switches. Our test program has demonstrated this level of durability in these basic elements. Capacitors of sufficient energy density have operated for over 500 million shots continuous at 55 Hz.¹⁶ (We simultaneously tested eight capacitors and experienced no failures). Magnetic materials have been developed by the electrical power industry with lifetime in excess of 1 billion shots. The switches are based on an APP (Applied Pulsed Power, Freeville NY) model S-33A-12 switch, which is a commercially available product.¹⁷ Each switch is composed of twelve modules and eight of these modules have been operated continually at 20 Hz for more than 300 M shots at full Voltage (4 kV).¹⁸ We have recently completed an all solid state, 12 stage, 250 kV Marx generator using these components. The system has run over 1 Million shots at 5 Hz with an overall efficiency of $> 80\%$. This will be used to develop and evaluate cathode concepts. A replacement 20 kJ pulsed power system based on these components is now under design.

Electron Beam Source (cathode): The electron beam current must rise and fall quickly and be spatially and temporally uniform. Our work has concentrated on cold (field emission) cathodes owing to their simplicity, robustness, practically zero power consumption, ability to operate at ambient temperatures, and relatively modest vacuums requirements (10^{-4} Torr). One approach is to place a ceramic honeycomb structure in front of the primary emitter surface.¹⁹ The ceramic improves the uniformity, decreases the rise and fall times, reduces the post shot evolved gas, and extends the lifetime of every cathode we have evaluated. While there are several mechanisms at play, the dominate one is that the capillaries in the honeycomb provide a plentiful source of secondary electrons that generate a plasma that electrically connects the emitter/ceramic gap within a few nanoseconds. Thus the main source of beam electrons comes from the inside of the capillary wall, and not explosive emission from the emitter. This significantly reduces erosion from the cathode with a concomitant increase in lifetime. A second type of cathode is made of carbon fibers pyrolytically bonded into a carbon substrate. These do not have the spectacular uniformity of the ceramic, but they are sufficiently uniform and are less expensive. This type cathode has demonstrated over 500,000 shots at 2.5 Hz without failure.

Electron Beam Transport and Deposition: We have made several advances in electron beam transport and deposition. On Nike we identified and eliminated a transit time instability characteristic of large area, low impedance cathodes. The instability imparts an axial velocity spread to the electron beam that lowers the energy transfer efficiency into the laser gas. Modeling with a particle in cell (PIC) code,²⁰ followed with experiments showed the instability can be mitigated either by slotting the electron beam cathode and loading the slots with microwave absorbing material²¹ or by using the ceramic honeycomb cathode described above.²²

On Electra we demonstrated that the electron beam can be patterned into strips so the beam “misses” the hibachi ribs. The topology of the strips can be empirically determined on Electra, but the predictive capability needed to design larger systems requires a full 3-D PIC simulation of the exact experimental geometry, including the rib structure, laser gas, and magnetic field. This was achieved with the Large Scale Plasma (LSP) code developed by Voss Scientific. The simulations accurately predict both the cathode counter rotation angle and the energy deposition efficiency.²³ Net transmission efficiencies from cathode to laser gas of up to 75% have been demonstrated on Electra.

We use several 1D codes to predict the electron beam deposition in the gas. These include transmission and scattering through the foil and backscattering in the gas. These have been used to accurately predict the observed energy deposition in the laser gas,²⁴ as well as in the hibachi foil.²⁵ The latter is essential for designing foil thermal management systems.

Hibachi: Durability of the hibachi foil is one of the remaining challenges. Up until recently the continuous run lifetimes were limited to about 10 to 20 thousand shots. It was discovered that these failures were associated with voltage reversals after the main pulse. We believe that the reversals initiated electron discharges (cathode spots) that “drilled” small holes in the foil leading to premature failures. By increasing the anode cathode spacing these failures were eliminated. More than 90,000 continuous shots have now been achieved at 2.5 Hz with Electra operating as a laser.

The present system is very reliable at 2.5 Hz. The main additional challenge at 5 Hz is sufficiently cooling the foil. In the baseline Electra configuration that is accomplished solely by the recirculation of the laser gas. In conjunction with the Georgia Institute of Technology²⁶ we have developed an efficient technique to more effectively cool the pressure foil. A linear array of gas jets is arranged to blow recycled laser gas directly on the foil. Prototype experiments on Electra showed the foil

temperature was kept at 370 deg C, which is well below thermal fatigue limit of 480 C over a 50 shot run at 5 Hz. See Fig. 6. No degradation in the focal profile of a probe laser beam was observed during this run. (The probe resolution could detect 10 XDL perturbations).

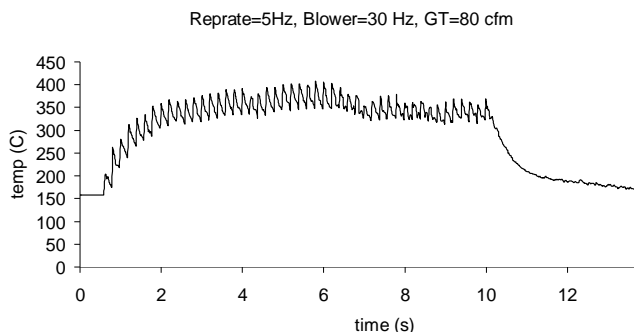


Fig. 6 Foil temperature (taken with a pyrometer) during a 5 Hz, 50 shot run.

KrF Physics Code: We have developed a KrF physics code, called Orestes, to design future KrF laser systems. Orestes includes the electron deposition, plasma chemistry, laser transport and amplified spontaneous emission (ASE). The code follows over 22 species, 130 reactions, two excited electronic states of KrF*, and 53 vibrational levels. The code accounts for the e-beam input, laser input, plasma thermal and internal energies, the Amplified Spontaneous Emission (ASE), and the laser output. Orestes accurately predicts the laser output of several different KrF laser systems over a wide range of conditions. It includes pulse shaping capability, and should be able to prescribe how to generate the pulse shapes for both conventional and shock ignition targets.

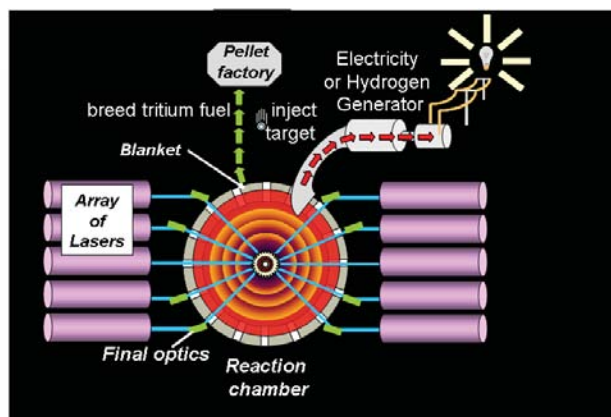


Fig. 7 A laser fusion power plant.

IV. A FUSION TEST FACILITY

Figure 7 shows schematically the principal components and functions of a laser fusion power plant.

Few mm diameter spherical "pellets" containing frozen DT fuel are injected into the ~8 meter inner radius target chamber at ~5 Hz. The energy from numerous laser beams symmetrically illuminates each pellet, and the energy from the fusion reactions are absorbed in a "blanket" contained in the walls. Heat from the blanket then is available for electrical power or hydrogen production. Neutrons transmute a portion of the lithium contained in the blanket to tritium to replenish the fuel supply. The primary mission of the FTF is to develop all the technologies, components, and functions with the exception of net electrical power generation. However, if the high gains predicted for shock ignition are achieved, the FTF could in principle DEMO power generation.

The standard metric for pellet gain in a fusion power plant is that the product of the gain times the wallplug efficiency of the driver needs to be at least ten. For the case of KrF with projected 7% wallplug efficiency that minimum gain is about 140. As can be seen in Fig. 1 this gain requires minimum laser energies of about 0.5 megajoules (with shock ignition) to ~2 megajoules (with conventional direct drive) Economics of scale in power generation might cause one to use higher driver energies. The FTF does not need as high gain, and only needs to generate enough fusion power in the reaction products to test materials, components and systems. These reaction products include energetic neutrons, x-rays, and ions including alpha particles. Because the fusion reaction is effectively concentrated into a point source, one can achieve very high fluxes with the FTF by placing test components closer to the reaction than the chamber walls. The FTF can thereby match or exceed the flux encountered in a full size power plant at much lower power. *The vision here would be to construct the FTF conservatively in regard to blanket and wall loadings, yet have the opportunity for high flux testing as described above.* A FTF generating about 100 MW should be adequate for this purpose. A 1 GW electric power plant would need to produce around 2.5 GW in fusion power to allow for conversion efficiency and other losses. As the loading on the first wall is the fusion power divided by area, prototypical wall loadings would be attained in the FTF by reducing the chamber radius by a factor 5 compared to a GW power plant. Reducing it instead by a factor of 2 would lower the FTF wall loading by a factor of 6, and thus achieve the testing objective.

The Fusion Test Facility described in reference 1 utilized the ~60× gain from high velocity implosions to achieve a projected 150MW fusion power (thermal) output with a 500 kJ driver. If successful, shock-ignited targets might achieve the gains needed for power production at this driver energy. Alternatively one could consider a smaller FTF driver. 100x gain with a 5 Hz 300 kJ driver would also produce 150 MW of fusion thermal

power. This lower energy should be adequate, but somewhat marginal, for ignition and moderate gains ($\sim 20\times$) with high velocity implosions. However the higher laser energy option would of course be the more conservative and flexible route, and that is the one that we recommend.

V. FUSION TEST FACILITY CONFIGURATIONS

In this section we briefly discuss a few details of the FTF and its applications. The laser driver system described for the FTF in reference 1 is an angularly multiplexed systems utilizing twenty 28 kJ KrF amplifiers. Ninety 2.5 ns FWHM beams extract energy from each of the amplifiers. These beams are grouped into 40 clusters that uniformly illuminate the target. The clustered beams take up less than 2% of total solid angle, so there is ample room to accommodate test objects within the chamber. In the next section we present an alternate configuration for the final KrF amplifier that would use the same type of optical system.

Figure 8 (similar to Fig. 10 in reference 1) illustrates how large test objects might be distributed in the FTF target chamber at distances 1 meter and 2 meters from the target. The displacements per atom (dpa's) are calculated at fusion powers of 50 and 150 MW assuming 70% of that power is in the energetic neutrons and that the facility operates 60% of the time. The dpa's per year for relatively large test objects can exceed 10, while the first wall receives a modest 2 dpa. The volumes for test at high neutron fluxes (up to 50 dpa) greatly exceed that for proposed accelerator based systems such as IFMIF. These higher available test fluxes with lower chamber wall loading are a result of the " $1/r^2$ " dependence that is characteristic of an inertial fusion source. This is not possible with the distributed sources characteristic of magnetic fusion devices. Fission reactors can provide high flux densities and powers. However the fission neutrons are much lower energy, and cannot replicate the ratio of transmutations that can occur with 14 MeV neutrons from DT fusion. In particular there is concern about the formation of He bubbles in materials due to transmutations. The FTF would thus have a unique capability to test fusion materials and components.

In addition to the longer term damage from neutrons, the inner wall of an inertial fusion reactor can be damaged by the charged particles and x-rays emitted by the target. Since the reaction is pulsed, the instantaneous power levels are much higher than the average power. For the case of neutrons, which are primarily deposited within large volumes of material, this is not a serious issue and may even be an advantage in some instances. However the charged particles and x-rays will be deposited within a thin layer on the first wall and care must be taken that

they do not ablate or otherwise damage the surface. One solution under consideration is to use low activation ferritic steel with an engineered thin refractory tungsten coating to deal with the surface heating by these particles. The structure of this engineered could prevent exfoliation from alpha particles penetrating the surface and forming bubbles. Use of magnetic fields and other means to protect the surface are also under consideration. These schemes would also be used to help prevent surface damage to test objects undergoing long term neutron irradiation.

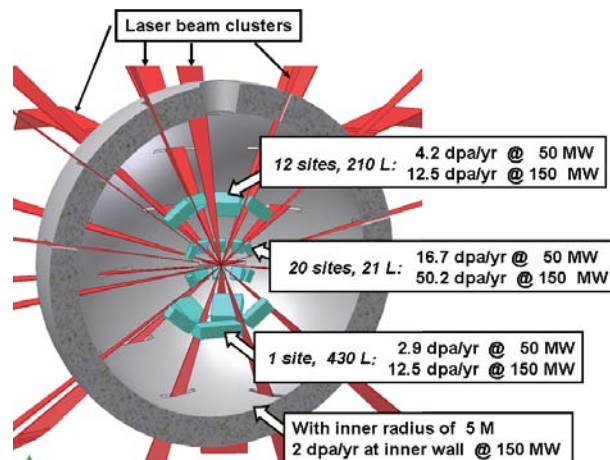


Fig. 8. Available sites for locating test objects in the FTF target chamber between beam clusters. Here the laser beams are arranged into 40 clusters and the objects are one and two meters from the target.

As discussed in reference 1 the FTF would utilize sufficient tritium that it needs to breed it via transmutation of lithium in the blanket. Typically the breeding ratio is 1.1 to 1.2. This requirement limits the solid angle subtended by objects thick enough to stop neutrons to be less than about 10% of 4π . Breeding sufficient tritium is an essential technological development for power plants that employ DT as fuel. Once material and component issues are resolved, one could consider redirecting the laser beams into a smaller diameter chamber where the neutron fluxes at the wall match the levels desired for a power plant.

VI. DEVELOPMENT PLAN

There is the question of how to get from the present level of scientific and technological development to an FTF. We will first deal with two particular issues, the laser development and target design, and then present an overall plan.

VI.A. KrF Amplifier for the FTF

In reference 1 the FTF used a nominal 28 kJ final amplifier that employed segmented cathodes. This type configuration is desirable for amplifiers of this size and scales to much higher energies. A 50 kJ module is described elsewhere.²⁷ However, since the FTF has modest energy requirements we are evaluating simpler designs that utilize two-sided pumping from monolithic cathodes as used in Nike and Electra. Figure 9 shows a size and parameter comparison between the Nike final amplifier and a new baseline FTF amplifier configuration. The 60-cm aperture width is increased to 100 cm, and the voltage from 600 kV to 800 kV. Nike has demonstrated 5 kJ output, and simulations indicate that it could reach 8-9 kJ when the highly transmissive hibachi configurations used for Electra are installed. The FTF amplifier would employ approximately the same diode current as Nike, but uses higher voltage to accommodate the wider gas cell. The higher voltage also helps reduce losses due to electron beam deposition in the pressure foil. Simulations accounting for the electron beam transmission and the

laser kinetics predict a little more than 17 kJ output. If one rates it as 16 kJ, and assumes 90% of the light is transmitted to the target chamber, then 35 amplifiers would provide enough energy for a 500 kJ FTF. A conservatively designed system might employ 40 amplifiers to allow redundancy and opportunity for individual amplifier servicing without halting the full FTF system. This amplifier count could be compared with the 48 quad beam amplifiers employed in NIF. The angularly multiplexed optical configuration of the FTF would remain similar for that described in reference 1, except the beam count is higher due to use of the smaller final amplifiers. This is not judged to be an onerous complication because the area of the total optics remains the same and the beams would be bundled into the same number of clusters at the target chamber. The rectangular shape of the beams in this configuration more naturally matches the geometry of commercial discharge pumped amplifiers needed in the front end, and it also better matches the grazing incidence metal mirrors that are under evaluation as a neutron damage resistant final optic.

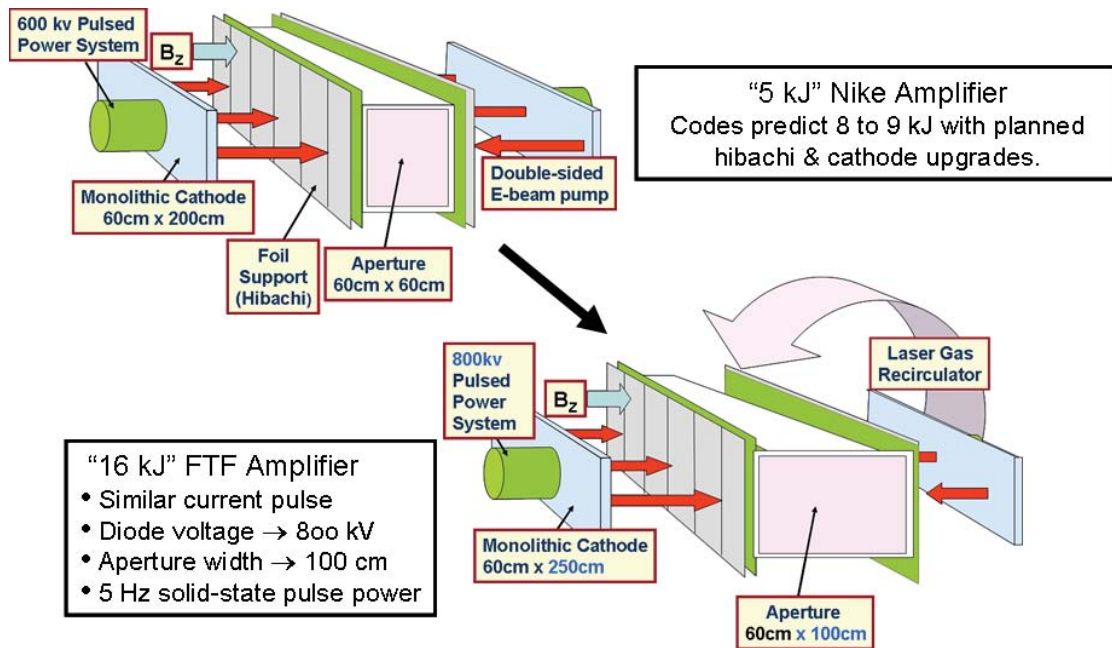


Fig. 9. Our new FTF final amp design is a modest scale-up of Nike’s 60-cm amplifier. It will use solid-state switched 5 Hz pulse power developed on the Electra facility.

VI.B. Target Design and Physics

The FTF target designs that were presented here are based on hydrodynamic simulations where the code has been extensively tested against experiments and independently developed codes. Therefore, within the constraints of hydrodynamics modeling of the implosion physics, the results described here are most likely accurate and reliable. The main physics issues that affect

the results that are not resolved by a radiation-hydrocode involve high intensity laser plasma interactions. To some extent these missing effects can be modeled by theory and kinetic or particle in cell (PIC) simulations. However, the bottom line can only conclusively be settled by experiment. The Nike facility will be able to reach the intensities envisioned for FTF targets with energies up to

a few kJ. The development path we present below calls for building of a prototype full scale 16 kJ FTF beamline. This beamline would allow higher energy KrF laser target interaction experiments, and that should resolve this issue prior to constructing the FTF. Note that both the NIF and LMJ will allow LPI experiments at energies beyond those envisioned for the FTF, but at longer laser wavelengths ($\lambda = 351$ or 526 nm). Improvements in simulations could allow us to scale to the FTF from these results.

VI.C. The 3-Stage Plan

Figure 10 shows a 3-Stage plan that provides a roadmap from the present level of development to prototype laser fusion power plants.

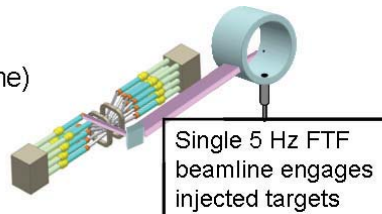
In Stage I all the technologies and full scale modular components for an FTF are developed. A centerpiece of Stage I is an integrated facility where a single 16 kJ beamline of the FTF is directed to a target chamber. The beamline would consist of approximately 100 160-J beamlets that are angularly multiplexed through a full size KrF electron-beam pumped FTF main amplifier. This facility would develop all the laser beam characteristics needed in the FTF including precision focal profiles, temporal zooming of the focal profiles and the pulse shapes required for the candidate pellet designs. Surrogate targets would be injected into the vacuum chamber and engaged by the focused beamlets with the

precision required for the FTF. The integrated facility would thereby develop and demonstrate several essential capabilities. Other Stage I activities include development of low cost cryogenic target fabrication, continued refinement of the target designs, implosion experiments on large single shot facilities such as NIF, development of chamber and optical materials, and detailed design of the FTF system and development of its components.

In Stage II the FTF is built and operated. The initial operation would be at modest repetition rates, perhaps 10's of shots per day, to allow refinement of the targets designs. As the facility ramps up to full operation, it would be used to test and develop materials, components and procedures for future power plants. With successful development and testing of materials, systems and procedures with the FTF, the technical basis for designing follow-on prototype power plants would be available. If the economics are favorable, then industry should be able to take the lead in Stage III, construction of one or more prototype power plants. We estimate that Stage I would take 5 years and an additional 6 years would be needed to build the FTF. If this Staged program were initiated in 2011 the FTF might then be operational in 2022. Its initial operation would then be following a projected 12 years of experience with ignition experiments on the National Ignition facility.

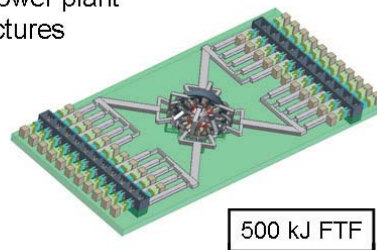
Stage I : Develop full size components

- Laser module (16 kJ 5 Hz KrF beamline)
- Target fabrication/injection/tracking
- Chamber design
- Refine basic pellet physics



Stage II Fusion Test Facility (FTF)

- Demonstrate physics / technologies for a power plant
- Develop/ validate fusion materials and structures
- Operating: ~2022
- Significant participation by private industry



Stage III Prototype Power plant(s)

- Electricity to the grid
- Transitioned to private industry

Fig. 10. A 3-Stage development plan for laser fusion energy.

VII. CONCLUSIONS

A laser based Fusion Test Facility continues to look very attractive towards developing and deploying fusion energy. The latest target designs utilizing shock ignition hold promise of higher gain for the FTF, and could

substantially reduce the driver size for future power plants.

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